

Moon Diver: A Discovery Mission Concept for Understanding the History of Secondary Crusts through the Exploration of a Lunar Mare Pit

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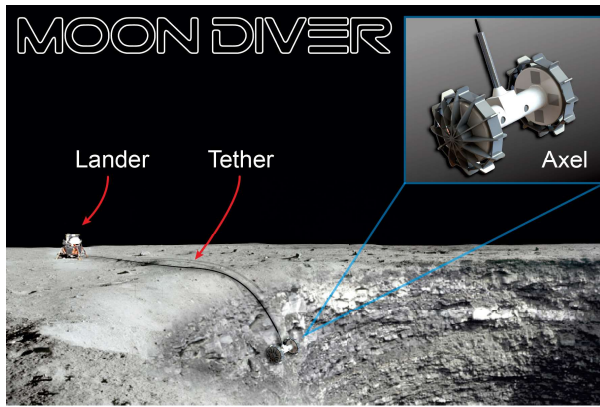


Figure 1: Concept for the Moon Diver Mission.

Abstract—When the Apollo astronauts collected samples from Tranquility Base in 1969, they provided an unprecedented window into the processes that shaped the Moon. Ever since, the Moon has served as a “keystone” for understanding planetary geological processes throughout the Solar System. Like all samples that have been returned from the Moon, the Apollo 11 samples were collected from the lunar regolith, a layer of jumbled and pulverized rocks that blankets and obscures the Moon’s bedrock geology. When geologists reconstruct the history of the Moon, these samples are like scattered puzzle pieces, each representing important information, but removed from the context of their formation and isolated from the bigger picture of how the Moon’s crust was formed.

The goal of Moon Diver is to return to Mare Tranquillitatis, taking advantage of the discovery of a natural pit cave entrance exposing a deep cross-section through both the lunar regolith as well as tens of meters of bedrock lava layers. Collecting information on the chemistry, mineralogy, and morphology of these intact bedrock layers would allow us to investigate where rocky crusts come from, how they are emplaced, and the process by which they are transformed into the regolith layer that we see from space. In doing so, the mission would combine the deep knowledge gained by Apollo with the unprecedented *in situ* access to secondary crust granted by the lunar mare pit to understand these fundamental processes on the Moon, and to use this knowledge as a keystone for understanding the same processes across the Solar System.

The success of the Moon Diver concept hinges on accessing the subsurface. The existence of the mare pit provides a cross-section through the lunar maria. Access to the record exposed in the wall of this pit is provided by two critical space technologies: pinpoint landing (allowing the delivery of the payload close to the pit) and extreme terrain mobility (allowing the delivery of capable instruments to the cliff wall). Pinpoint landing is a closed-loop guidance and navigation capability that repeatedly matches visual features from a downward-facing camera to *a priori* acquired terrain maps. This body-relative navigation is then used with closed-loop control to guide the spacecraft toward its landing target, yielding a tight landing ellipse. Once on the surface, an extreme-terrain robotic explorer, called Axel, would egress from the lander and traverse tens of meters to the pit. The lander provides mechanical support, power and communication to the rover through its umbilical tether. Anchored to the lander, the two-wheeled, tail-dragger rover would pay out its tether as it traverses toward the pit. With the aid of its 300-meter tether, the rover can traverse

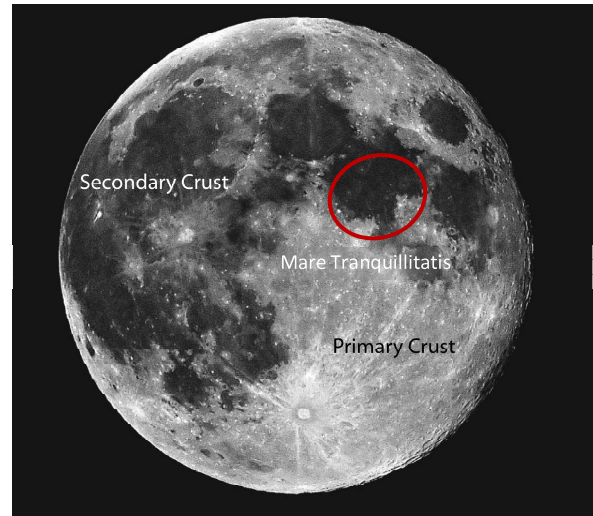


Figure 2: The primary and secondary crusts of the Moon. Mare Tranquillitatis is an example of a classic secondary crust composed of low-viscosity flood basalts.

the steep slopes of the pit funnel and rappel its vertical walls. The rover carries a surface preparation tool together with a suite of three instrument types: (a) a trio of high-resolution cameras (Mars 2020’s EECAMs) for acquiring context images of the near and far walls with the near-wall pair in a stereoscopic configuration, (b) an alpha-particle-X-ray Spectrometer (MSL’s APXS) for elemental composition, and (c) a multi-spectral microscopic imager (MMI) that uses controlled lighting for mineralogy. The surface-preparation tool removes dust and patina that may be present on the rock wall by grinding a small area. The surface-preparation tool, the MMI and the APXS would be deployed from their instrument bays in one of the wheel wells. The rover would independently point each of its instruments at the same target of interest on the wall with millimeter-level repeatability. Confidence in the technologies of pinpoint landing and extreme-terrain access is based on helicopter testing of terrain-relative navigation and field testing of extreme terrain mobility respectively. The latter was tested using Axel rover prototypes with integrated science instruments at multiple terrestrial analog sites including a basaltic pit in Arizona.

Landing shortly after sunrise, the surface mission timeline is just shy of a lunar day (14 Earth days). Upon landing, the rover would egress from the lander, traverse toward the pit, descend along the pit funnel and rappel down its wall. Throughout its traverse, the rover would acquire multiple measurements of both regolith and mare layers. After descending to the bottom of the layers, the rover will reach a significant overhang. This void space may open into a large cave or lava tube, which could someday provide a protected location for a lunar base. For these reasons, lunar pits provide an exciting new target for lunar exploration.

The information presented about the Moon Diver mission concept is pre-decisional and is provided for planning and discussion purposes only.

TABLE OF CONTENTS

1. INTRODUCTION.....	3
2. SCIENCE DESTINATION.....	4
3. SCIENCE INVESTIGATION	4
4. INSTRUMENT PAYLOAD.....	6
5. TARGET ENVIRONMENT.....	6
6. GETTING TO THE LUNAR PIT	9
7. THE AXEL SYSTEM.....	11
8. THE AXEL ROVER	11
9. CONCEPT OF OPERATIONS	16
10. SUMMARY.....	16
11. ACKNOWLEDGMENTS.....	16
12. REFERENCES	16
13. BIOGRAPHY	18

1. INTRODUCTION

Background

Subsequent to the chaos of accretion and differentiation, the rocky bodies started to evolve, primarily through the formation of “secondary” crusts composed of volcanic material [1][2]. Vast volcanic outpourings served both to resurface the planets and to advect heat from the interior. Secondary crusts are the most common type of crust in the Solar System [3]. On Earth, parts of the secondary crust have been recycled by plate tectonics, eventually forming a “tertiary crust” composed of evolved, continental materials [1]. On Mars, Venus, and Vesta, the basaltic secondary crust still dominates the body, serving as the canvas upon which all of the other geological processes take place [1]. The Moon is unusual in that it retains both its primary and secondary crusts: the lunar highlands and maria, respectively (Figure 2). The Moon is an ideal place to study secondary crust formation because its crust is well preserved, it has been

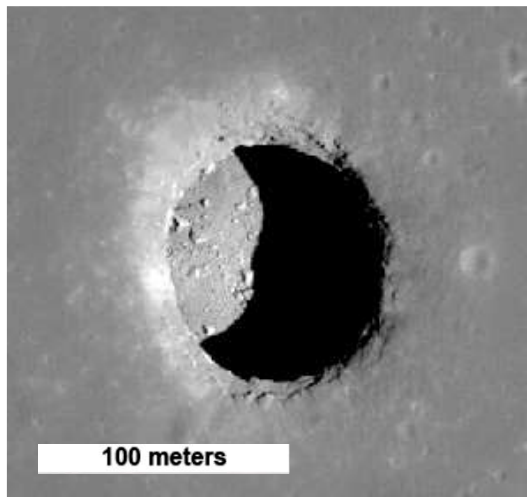


Figure 3: The Mare Tranquillitatis Pit at (8.335° N, 33.222° E). Credit: NASA LROC NAC M126710873R (0.5 m/pixel resolution)

subject to relatively few confounding geological processes (for example, water or wind), and the surface is relatively accessible (compared to Venus or Mercury) [4][5][6][7]. Until recently, however, a more complete understanding of the Moon’s secondary crust was hampered by the near-ubiquity of the lunar regolith, which prevented the direct examination of in-place bedrock stratigraphy. However, the discovery of lunar pits by the JAXA SELENE/Kaguya mission [8] and subsequent observations by NASA’s Lunar Reconnaissance Orbiter [9][10] revealed tens of meters of pristine, bedrock stratigraphy, offering a unique opportunity to directly access the basaltic layers.

Overarching Science

The goal of the Moon Diver mission concept is to better understand the fundamental process of secondary crust formation by studying the origins, emplacement processes, and evolution of the Moon’s secondary crust (the lunar maria).

Enabling Capabilities

Pinpoint landing and the Axel extreme terrain rover would enable the Moon Diver mission concept. After the spacecraft lands within less 100 m from the edge of the pit, the Axel rover traverses and ingresses into the pit, acquiring measurements along its near-vertical wall. The Jet Propulsion Laboratory has been developing both capabilities for several years.

The vision-based capability for pinpoint landing uses terrain-relative navigation to repeatedly match visual features from a downward-facing camera to an *a priori* terrain map. This navigation information is used to guide the spacecraft toward its landing target, for a tight landing ellipse.

Once on the surface, the Axel extreme-terrain robotic explorer would egress from the lander. Axel is a two-wheeled tail-dragger with a tether that is anchored to the lander. It carries hundreds of meters of tether that it pays out as the rover traverses away from the lander. With the aid of the tether, the rover can rappel down steep slopes using the same principle of motion as a yo-yo. The rover carries two large hubs covered by the wheels, which can house three to four instruments each. By coordinating its four actuators (wheels, tail and spool), the rover is capable of pointing its instruments with more than adequate repeatability while supported by the tether. The lander provides mechanical support, power and communication to the rover through its tether. The 50 kg Axel rover prototype has clocked over a kilometer of mobility in field tests in California and Arizona and has traversed near vertical slopes.

Surface Mission

The mission timeline is one lunar day (14 Earth days) for rappelling and acquiring context imagery along a transect and its opposing wall, collecting microscopic imagery under controlled lighting for mineralogy, and acquiring Alpha-

particle-X-ray spectroscopy for elemental composition. The instruments as well as a surface preparation tool would be deployed from the instrument bays.

Lunar mare pits may open into deep subsurface void spaces or lava tubes. The Tranquillitatis pit opens onto a void that extends back under the surface a minimum of 25 m [10]. In addition to their scientific interest, lunar caves could provide a favorable geometry for a lunar base, as they would be naturally protected from radiation, micrometeorites, and temperature swings. The Moon Diver mission would enable us to peer into the void and assess the feasibility of such an architecture. In this way, Moon Diver helps us understand the Moon's past while preparing for its future.

2. SCIENCE DESTINATION

Why Lunar Pits?

The key advantage sought by Moon Diver is access—unprecedented access to a stratigraphic section all the way through the regolith and to a sequence of unique bedrock lava layers. The Moon provides the best environment for this study because it offers classic examples of both regolith and lava layers in an environment that is protected from competing geologic processes such as tectonic activity, wind and water erosion.

Lunar pits are ideal because they provide access to layers; but they are not the only location where layers are exposed on the Moon. Other layered sequences have been discovered by the Lunar Reconnaissance Orbiter Camera (LROC) in the walls of large craters. While also scientifically interesting, these exposures are less desirable because the impact process may shock, break, or even occasionally invert these layered sequences. The effects of the impact process would have to be understood and removed in order to understand the sequence that they expose. Lunar pits, on the other hand, form via collapse [10]. In this case, layers of lava are deposited over a lava tube or fissure. As the lava tube roof progressively collapses (or the fissure widens), material cascades into the void, causing a collapsed pit. This process has been observed on Earth [12] and the layers in the wall of the pit are preserved precisely as they were during their emplacement.

Why Mare Tranquillitatis?

After the initial discovery of the lunar mare pits by JAXA's Terrain Camera on SELENE (6 m/pixel), ten lunar pits were discovered by LROC [9][10], including seven in the nearside mare deposits, two in the highlands, and one on the far side in Mare Ingenii. The lunar pit in Mare Tranquillitatis is an especially tantalizing target: sitting above one of the largest confirmed void spaces, it also exposes one of the largest vertical extents of layers of the mare pits. Critically, it is located on the boundary between two distinct Tranquillitatis lava types that have been correlated with samples collected by the astronauts on Apollo 11 [13]. This means that when the Moon Diver payload identifies a lava in cross-section at the

Tranquillitatis pit, 50 years' worth of Apollo analyses can immediately be leveraged.

3. SCIENCE INVESTIGATION

Understanding Secondary Crust Formation and Evolution

In order to understand secondary crusts, we must understand three separate processes: first, where the magma that forms the crusts comes from; second, how it is emplaced onto the surface, and third, how this crust is subsequently changed by other processes (i.e. regolith formation, affecting our ability to interpret it from orbit).

Moon Diver's goals and objectives are as follows:

Goal 1: Interior Composition: probe the interior of a terrestrial planetary body by determining the composition of one of its primary magmas.

- *Science Objective 1: Determine the composition of the source of the mare basalts at Tranquillitatis.*

In order to properly interpret a volcanic deposit, one must be able to separate the influences of its three stages: generation, ascent, and eruption [2] [4]. For example, to accurately assess the composition of a volcanic source, the ideal sample to measure is one that rapidly transited through the crust without stopping, and then chilled immediately to a glass upon erupting before any of its components had a chance to separate. This lava would represent a "primary" composition [14]. More commonly, a lava will experience some fractional crystallization either on the way up or as it flows on the surface. To get the primary lava composition, we have to average all of the "derived" compositions that we see in the final rock (e.g. crystals that solidified first and a surrounding matrix that solidified later). Abundances of key elements can reveal whether the lava was contaminated by crustal material as it ascended, whether it melted early or late in the history of the magma source, and many other facets of lunar petrology.

When the Apollo astronauts collected samples on the Moon, they were collecting loose fragments from the regolith. They could not be sure whether they were collecting samples that were representative of primary magmas or rather differentiated lava from the same flow, because they could not see the rest of the flow that the sample came from; whether it ascended quickly or slowly, or whether it differentiated as it cooled in place. By accessing exposed stratigraphy of a sequence of lavas and studying them exactly as they looked when they cooled, the Moon Diver mission can understand the lava emplacement process and how it affects the estimation of the composition of the Moon's primary magmas.

Goal 2: Emplacement Process: understand emplacement regime of a planetary flood basalt.

- *Science Objective 2: Determine whether basalts were emplaced **catastrophically** in turbulent flows or **incrementally** in smaller but more numerous inflated flows.*

Secondary crusts are made mostly of basaltic lava, which forms when the primitive interior of a planet is partially melted [1][2]. On terrestrial bodies such as Venus, Mars, the Moon, and Mercury, the secondary crusts can be dominated by particularly extreme eruptions known as “flood basalts”. This type of eruption is characterized by voluminous outpourings of low viscosity lavas that form vast flat plains. Meandering channels called “sinuous rilles” and extremely long lava flows imply that flood basalts could have been emplaced in a turbulent rather than a laminar regime on the Moon in contrast to modern flood basalts on the Earth [15]. Flood basalts are important because they are the primary way that planetary bodies are resurfaced (by area). Since they represent large amounts of lava and gas extruded over geologically short periods, they can also have profound effects on a planet’s atmosphere (even potentially giving the Moon an atmosphere for tens of millions of years [16]). While there has not been a flood basalt eruption on the Earth during human history, these volcanic events have been linked to massive climate perturbations, including the largest extinction event in Earth history (e.g. [17]). For these reasons, studies of the range of effusion rates and mode of emplacement for terrestrial flood basalts is a mainstay of modern volcanology. However, because of the lack of cross-sectional data for other planets, the effusion rate of extraterrestrial basalts remains unknown to several orders of magnitude, and their effects on their ancient atmospheres remain difficult to estimate [18][19]. Fundamental knowledge gained by studying the representative, classic, and well-preserved flood basalts of Mare Tranquillitatis on the Moon would advance our knowledge and understanding of the process of flood basalts emplacement throughout the Solar System.

Goal 3: Regolith Formation: understand how regolith develops from rock on an airless body.

- *Science Objective 3: Determine the extent to which the regolith is representative of the underlying bedrock as opposed to exogenous or allochthonous components.*
- *Science Objective 4: Determine the nature of the transition from regolith to bedrock*

The samples that we have from the Moon as well as most of our remote sensing data come from the uppermost layer of regolith. The process of regolith formation and space weathering is common among the majority of the airless bodies in the Solar System. In this way, the Moon has long served as our primary source of information about regolith formation processes and how observations of the regolith can be translated into understanding of the crusts beneath. Moon Diver offers the first opportunity to transit through the regolith layer on any planetary body, directly measuring

differences in composition and grainsize distribution with depth, and understanding how the regolith changes as we approach the interface with the underlying bedrock. This investigation would inform models of lunar regolith formation, and provide a keystone for understanding regolith processes on other airless bodies such as Mercury, asteroids, and many outer Solar System moons.

Measurements

Science Objective 1: Determine the composition of the source of the mare basalts at Tranquillitatis.

Three types of measurements are required to achieve this science objective: (1) images of the basalts, showing whether they are glassy or crystalline, and how the basalt varies from top to bottom (i.e., the missing context); (2) a measurement of the mineralogy of the basalt, which tells us about the temperature and pressure conditions present during crystallization; and (3) a measurement of the elemental chemistry of the basalts, including different mineral phases and how lavas in the section are different from one another.

*Science Objective 2: Determine whether basalts were emplaced **catastrophically** in turbulent flows or **incrementally** in smaller but more numerous inflated flows.*

Eight measurements are required to achieve this science objective: (1) the elemental and (2) mineralogical composition of the basalts, as above (to estimate their density and rheology); (3) images of their vesicle and crystal distributions (which also affects their viscosity), (4) images of the lavas from a distant vantage point to measure their thicknesses; (5) images used to distinguish their flow morphologies (which are proxies for their effusion rates); (6) small-scale flow textures and (7) rheological indicators (e.g. sheared vesicles); and finally, (8) the presence or absence of paleo-regolith layers, which would indicate a long hiatus in lava effusion.

Science Objective 3: Determine the extent to which the regolith is representative of the underlying bedrock as opposed to exogenous or allochthonous components.

Science Objective 4: Determine the nature of the transition from regolith to bedrock.

Five measurements are required to achieve objectives 3 and 4: (1) the chemical and (2) mineralogical composition of the regolith vs. depth and compared to the underlying basalts; (3) the presence and frequency of layers and the approximate size distribution in the grains that compose them, (4) the frequency of large grains and rocks mixed into the regolith with depth; and finally, (5) the frequency and orientation of fractures in the basalts (all provided by micro and context imaging).

Moon Diver achieves these measurements with a simple payload consisting of three context imagers (a stereo pair for

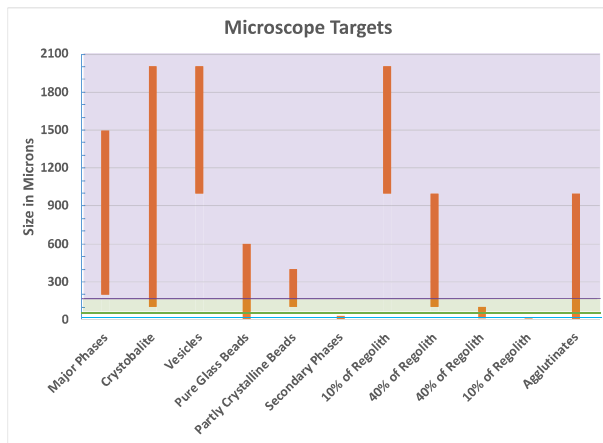


Figure 4: Size ranges of lunar microscope targets. With a resolution of 18 $\mu\text{m}/\text{pixel}$, targets are recognizable above 72 μm (four pixels) and their shape can be characterized above 180 μm (ten pixels).

the near wall of the pit and one camera to image the far wall of the pit); a multi-spectral micro-imager that spatially resolves small-scale crystals, vesicles, flow features, and regolith particles and spectrally resolves mineral signatures; and an alpha particle X-ray spectrometer, that measures absolute elemental abundances. This payload is described in detail below.

4. INSTRUMENT PAYLOAD

Context Imagers

The trio context cameras will be a re-fly of the Enhanced Engineering Cameras (EECAMs) currently being developed for the Mars 2020 missions [20]. They would be used as part of the baseline science payload to help understand the geomorphological context as well as serve engineering purposes: perceiving the environment, creating 3D topographic maps, assessing the terrain for mobility and guiding the rover through ground commands. The EECAMs are 20 mega-pixel cameras with color provided via an RGB Bayer filter pattern built directly on to the detector. Two of the cameras would be mounted on one side of the rover in a stereoscopic configuration and the third on the other side. The stereo cameras form a wide-angle FOV that is optimized for near viewing. While descending the pit wall, these cameras provide a resolution of $\sim 0.1 \text{ mm}/\text{pixel}$ and a full frame of 5120×3840 pixels. We would use these cameras to identify lava crusts and morphologies, which permits the determination between lava types, and to identify priority measurement spots for the other instruments. The third camera is optimized for distant viewing, with a narrower FOV. This camera is designed to image the far wall of the pit at a resolution of $4 \text{ cm}/\text{pix}$ (with the same full frame size) or better in order to measure the number and thickness of the lava layers.

Alpha-particle X-ray Spectrometer

The APXS is a TRL 9 instrument that has previously been flown on four Mars missions [21]. It uses a Cm^{244} source to

irradiate a target with X-rays and alpha particles, resulting in the production of characteristic X-rays through X-ray fluorescence and particle-induced X-ray emission processes to quantify specific elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Zn, Br, Rb, Sr, Y) [22]. The APXS spot size is 1.7 cm, and the integration time ranges from 15 minutes to approximately three hours, depending on the signal-to-noise ratio required for an individual measurement [23]. The bulk composition of the surface of a target can be inferred from APXS energy spectra, however, some uncertainty in the inferred composition of APXS energy spectra must be considered due to the averaging of particles or crystals of heterogeneous composition over the 1.7-cm spot size.

Multi-Spectral Microscopic Imager

The multispectral microscopic imager (MMI), serves a dual purpose as a microscope and a multi-spectral imager [24]. The MMI has a resolution of $18 \mu\text{m}/\text{pixel}$, allowing us to spatially resolve a variety of small lunar features, including pyroclastic beads, agglutinates, regolith particles, vesicles, and phenocrysts. To identify minerals, the instrument shines a suite of LEDs from $0.43\text{--}2.34 \mu\text{m}$ and records the reflectance of the surface with a broadband mercury cadmium telluride detector.

Surface Preparation Tool

The surface preparation tool provides a means to clear dust from surfaces as well as grind the targets of interest to remove the weathering patina. Removing dust will disambiguate the chemical composition and mineralogy of the regolith (composed of dust) from that of the target lava layers beneath. By pitching the body of the Axel rover, the grinder tool would create a relatively flat surface with a small area, which would reduce the time required to acquire measurements by the MMI, thus avoiding a large stack of images at multiple depths.

5. TARGET ENVIRONMENT

Mare Tranquillitatis

Located at 8.335° N , 33.222° E , the Mare Tranquillitatis pit (Figure 5) has been observed from several orbiting spacecraft. First discovered by the Terrain Camera (TC) on JAXA's SELENE spacecraft, this camera provided images at a $6 \text{ m}/\text{pixel}$ resolution compared to the M^3 (Moon Mineralogy Mapper's) $70 \text{ m}/\text{pixel}$ images. As of this writing, the highest resolution images of Mare Tranquillitatis are from the Narrow-Angle Camera (NAC) [9] aboard the Lunar Reconnaissance Orbiter (LRO) mission with a resolution of $0.5 \text{ m}/\text{pixel}$. Thermal images of this pit also exist from the LRO Diviner Lunar Radiometer Experiment, albeit at a low resolution of $200 \text{ m}/\text{pixel}$. The Mare Tranquillitatis pit has a diameter that ranges from $88\text{--}100 \text{ m}$, a depth that may exceed 107 m , and a wall height of about 75 m .

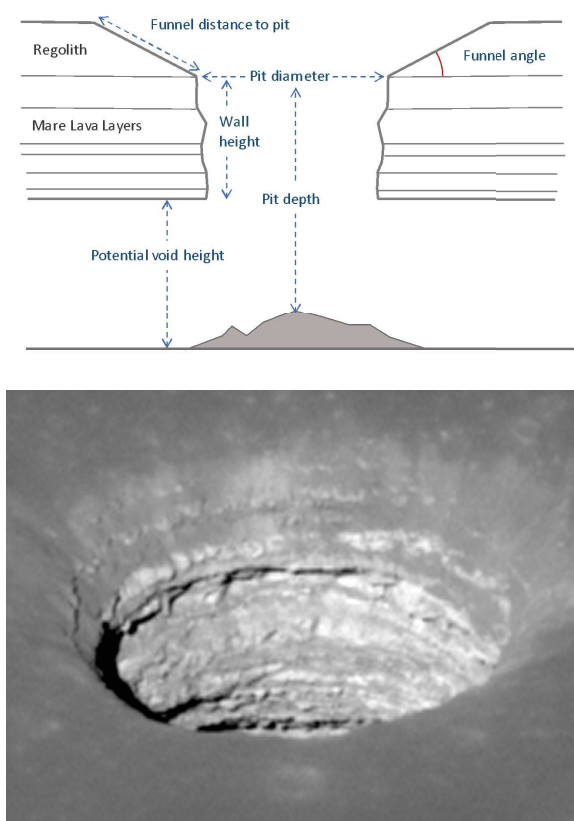


Figure 5: Cross-sectional diagram of a pit with key terminology identified (top), LROC image M144395745L of Mare Tranquillitatis Pit showing clear basalt layering (bottom) [11].

Topography

To understand the accessibility of the pit wall from a rappelling rover, first we need to reconstruct the highest resolution topography possible from all available orbital imagery. Second, we need to register the resultant dense 3D point cloud reconstruction to the local gravity vector to understand the global and local wall angles. A global wall angle of less than vertical (very steep but not overhung) allows for multiple wall contacts during rappelling, while a slightly overhung wall could separate the rover from the wall by several meters allowing only remote measurements including stereoscopic context imagery.

Both photogrammetry and photoclinometry techniques can be used to reconstruct the 3D wall topography. Here we will focus on the former but work is ongoing to further refine our topographic models. Generating the wall topography requires dense matching of features across multiple NAC images. For photogrammetric matching, the images that will be correlated need to have a proximal solar incidence angle to maintain a similar illumination and appearance and the wall must be illuminated. Moreover, the orbiter's trajectory has to be far enough to the side of the pit to obtain an oblique view of the nearly vertical wall. To date, the imagery that allows us to recover the pit wall topography is somewhat limited.

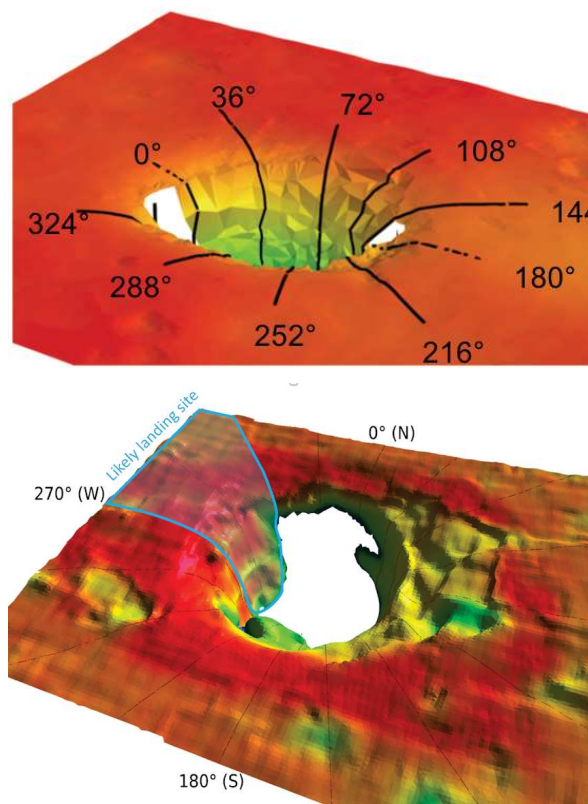


Figure 6: 3D reconstruction of pit wall topography using manually-matched features (top) (see citation [25]) and densely matched features (bottom) (0 degrees points North).

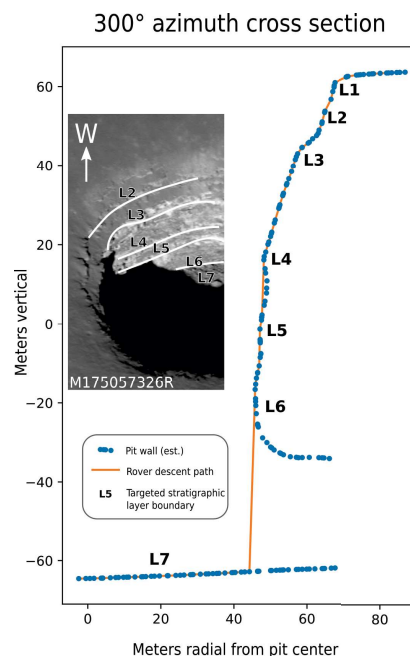


Figure 7: Cross section of the wall with layers correlated to LRO image M175053276R.

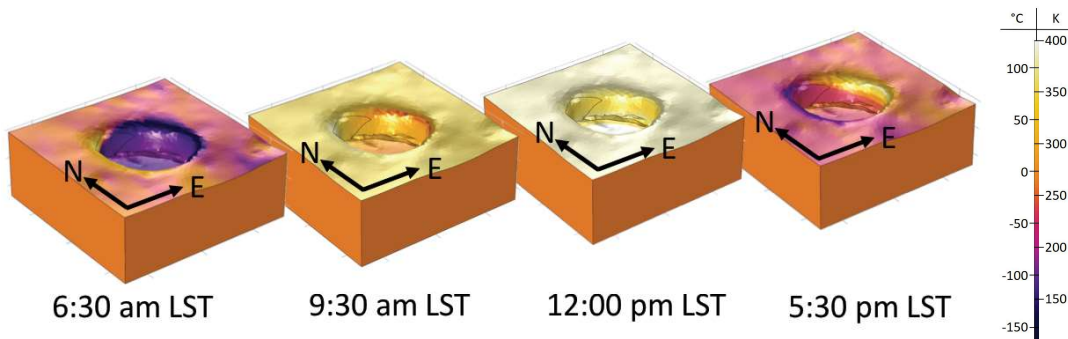


Figure 8: Temperature of the Tranquillitatis surface that is connected to a scaled pit topography using COMSOL multi-physics modelling tool (credit: T. Horvath, P. Hayne).

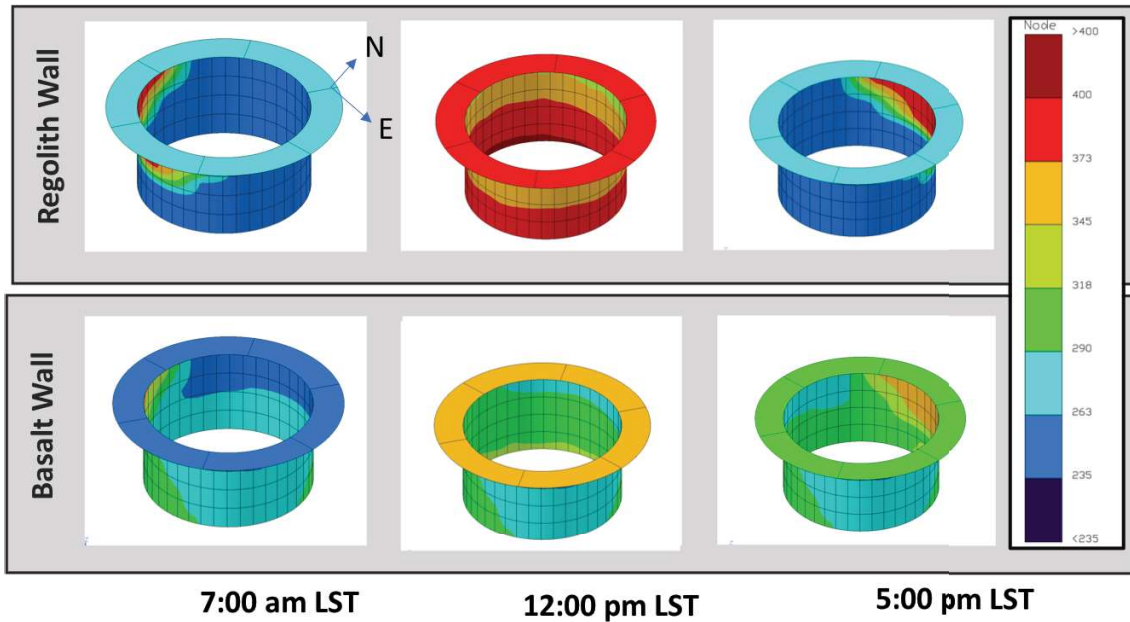


Figure 9: Comparison of pit wall temperatures using regolith vs. basalt properties.

Figure 6 (top) shows the reconstruction of the east wall by manually correlating points in a single pair of images [25]. Figure 6 (bottom) shows the reconstruction of the surface and pit walls (east and west) using automated dense stereo-matching algorithms. The dense reconstruction was generated from eleven LROC NAC images. To improve the fidelity of the 3D model, image information was used to correct both timing information and spacecraft attitude using bundle adjustment techniques. Reconstructing the west pit wall was particularly challenging due to the availability of only two NAC images, which were acquired at highly varying imaging geometries. A custom stereo matching algorithm was developed to handle images from two different vantage points.

Figure 7 shows a cross section of the north-west wall, where a rappelling rover would be in contact with nearly all the visible layers. This preliminary result is promising and shows sufficient contact with the multiple wall layers for the contact measurements. Future work will investigate the

uncertainty associated with these reconstructed surfaces and modeling the interaction between the rover and the wall, in particular, when transitioning between contact and free hanging. We will use both field experiments and dynamic simulations to inform our investigation.

Thermal

Understanding the thermal environment surrounding the pit is critical for the design of the thermal system for the rover (Figure 8). Close to the pit, the variations in temperature are complex and require detailed 3D thermal modeling. Figure 10 shows temperature variations across the diurnal cycle along different wall transects along the cardinal directions. With an east-west sun trajectory with an $\sim 8^\circ$ inclination, the south-most wall is permanently shadowed. The models show that both the south and north walls have a more tempered temperature rise/fall when compared to the east and west walls. The peak temperatures of the east/west walls are expected to be 25–40 K higher than the north/south walls

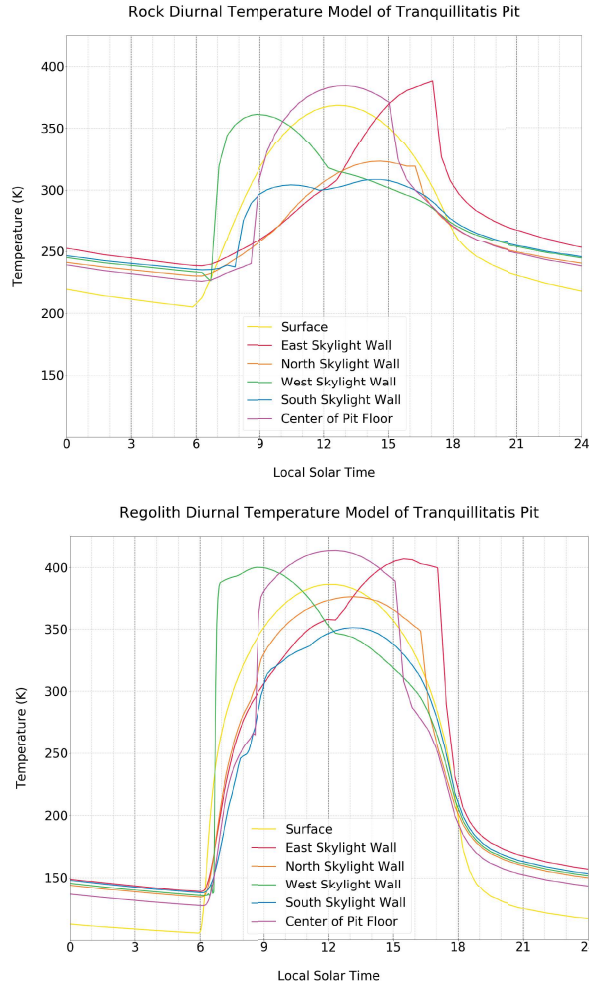


Figure 10: Temperature variations across diurnal cycles along north, east, south and west transects.

respectively, making the north/south walls more attractive targets from a thermal standpoint. However, the north/south walls have limited imagery and hence 3D topographic data. Data of the north wall is poorly resolved and no data is available for the south wall since it is permanently shadowed. Only portions of the north wall are visible from LRO's polar orbit.

Figure 8 shows the temperatures of the pit surrounding and the pit walls assuming regolith properties for both surfaces, across a lunar day. Temperatures of the surface surrounding the pit reaches ~385 K, while the pit wall and floor can reach ~410 K. Figure 9 compares the surface temperatures of regolith vs. basaltic pits. Modelling the pit wall using basalt rock properties reduces the peak temperature by 35–40 K when compared to pit wall surface made with regolith properties. Efforts to use different surface properties for the pit surrounding, pit wall and pit floor are ongoing. We expect that the basalt model of the pit wall to be more representative of what we would encounter. Due to the east-west solar motion, the west wall is hotter in the lunar morning and the east wall is hotter in the lunar afternoon, both caused by a low

solar incidence angle. Past noon lunar time, the pit edge casts a shadow along the west wall dropping its overall temperature.

While a specific landing target surrounding the pit has not yet been selected, landing west, north-west, or south west of the pit would offer several benefits. First, given that a portion of the lunar morning will be consumed by landing the craft, post-landing checkouts and deployments, stowed-rover checkout, rover egress, and site reconnaissance, the west wall would be cooler in the afternoon. Any contingency or delay in reaching the pit wall will continue to reduce the peak temperatures on the wall. Other benefits to landing west of the pit and driving eastwards toward the west wall include self-shadows that remain behind the rover as it approaches the pit, thus reducing the complexity of shadows in images. Should orbital imagery of the north wall become available from LRO, that will further relax the thermal requirements and open up approaches from the north of the pit.

6. GETTING TO THE LUNAR PIT

Lunar Trajectory

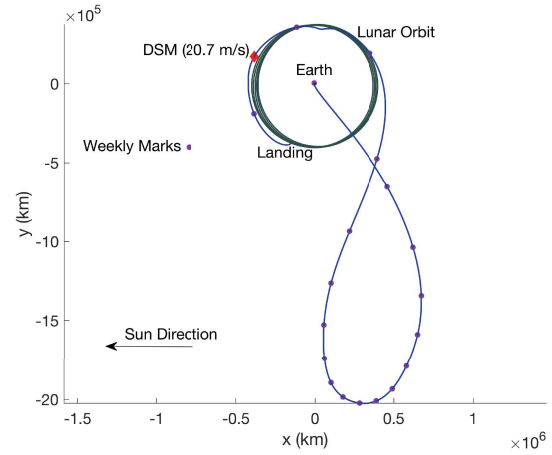


Figure 11: An example of a low-energy trajectory that could be used by Moon Diver, which includes a lunar flyby and a single deep-space maneuver.

If the Moon Diver Discovery proposal is awarded, it could launch on an Intermediate Low-performance class vehicle, such as an Atlas V 401, as early as 2025. The Lockheed Martin lander design is based on the successful Mars Phoenix and InSight landers, the designs developed for the MoonRise lunar lander proposed to New Frontiers, and the McCandless lander awarded recently under NASA's Commercial Lunar Payload Services (CLPS) program [26]. The lander stack consists of a solid rocket motor, the lunar lander, and the Axel rover that carries the science instruments. The stack would be inserted into a 130-day low-energy transfer to the Moon, which includes a lunar flyby and a single deep-space maneuver, leading to a planned arrival and landing later that year. Figure 11 shows an example of a Moon Diver reference trajectory in a Sun-Earth rotating frame. Using a low-energy

trajectory, the launch window has very few constraints, and the mission would be unaffected by selection for a later launch date.

The trajectory is designed to deliver the lander stack to a lunar arrival interface point located approximately 120 km to the north of the landing site in the Mare Tranquillitatis. The trajectory is designed for an early lunar morning arrival to maximize the lunar daylight hours for the surface mission, while at the same time allowing for sufficiently favorable illumination of the landing site during landing.

Approach, Descent and Landing

The Moon Diver mission requires pinpoint landing at a target landing site adjacent to the pit in order to enable access by a rover that remains tethered to the lander. The lander serves as the mechanical anchor to the rover, supplies it with power and serves as a communication relay between the rover and the ground through its link with the Deep Space Network.

To achieve a landing ellipse of less than 100 m, the descending spacecraft would employ terrain-relative navigation (TRN), whereby the lander compares images taken during the landing sequence with maps of the landing site stored onboard (constructed from images taken by orbiting assets such as Lunar Reconnaissance Orbiter) to establish its current position and chart a course to the landing site. The technologies to accomplish TRN for pinpoint landing on the Moon have been in development for several years and have been validated in a number of terrestrial flight tests. Moreover, the Mars 2020 mission is planning to use TRN for its landing sequence targeted for 2021. The Mars landing would serve as primary validation of the system prior to deployment on Moon Diver. Given the need for a lander vision system for TRN in the first place, both altimetry and velocimetry can be estimated additionally using a stereoscopic camera pair on the lander, leveraging thereby capabilities that have been deployed on several Mars surface missions. As such, the lander vision system is intended to replace the more-costly radar systems that are typically employed during the later stages of landing.

Following a final correction maneuver a few days before arrival, the lander stack approaches at a near horizontal flight path angle in a north-south direction relative to the lunar surface. To accommodate the approach path and allow for concurrent imaging, the camera is mounted at an oblique angle. Once the lander passes the lunar arrival point, the landing sequence is executed autonomously onboard the spacecraft. The solid rocket motor is ignited to decelerate and reduce the horizontal velocity. The lander's descent engines fire using pulse-width modulation to maintain the thrust direction. Following the solid rocket motor burnout, the motor is jettisoned and the lander performs a separation burn. Using a combination of inertial propagation and TRN measurements, the lander performs a trim maneuver to minimize downrange error that result from solid rocket performance dispersions. The latter is followed by a coast

phase at the end of which the lander reorients and starts its terminal descent phase. Using a combination of TRN, altimetry and velocimetry measurements together with onboard guidance, the lander continues to adjust its thruster firings to reach a low terminal vertical velocity. For the next tens of seconds, the lander descends at this constant vertical velocity, and upon sensing the ground, it shuts down the descent engines. Crushables in the three lander legs absorb the residual landing impact.

Delivering the Axel rover to the surface

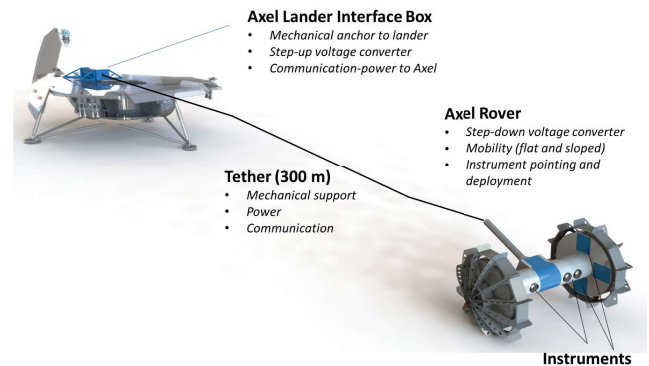


Figure 12: The Axel Rover with its instrument payload, the lander interface box, and the tether.

On the journey to the Moon, the Axel rover would be accommodated aboard the deck of the lander stack. After landing, the deck would sit approximately 1 m above the lunar surface. The rover would be mechanically secured onto the deck for launch and cruise and would also be electrically connected to the lander through its umbilical tether via an interface box. The latter would be secured to the lander and together they would serve as the rover's anchor during the surface phase. The interface box provides the mechanical anchor for the tether, a power converter to step-up the lander-provided bus voltage for efficient power transmission, and a communication interface board to connect to the lander's avionics box. Command to and telemetry from the rover is communicated through the tether, which carries redundant lines for power and communication to increase robustness.

Egress is provided via a ramp on the side of the lander, which enables Axel to rappel off the lander deck to the lunar surface in a controlled manner. The length of the ramp is such that Axel's wheels maintain contact with the lander until they transition to the lunar surface, even under conditions where a rock under a lander leg tilts the deck by 15°. Additionally, the ramp provides a reaction point for the boom to push against, allowing Axel and its boom to clear the lander. Once cleared, the rover would pay out the tether, lower its boom to the surface and drive away. Fairleads are provided at the outer edges of the lander deck and generous radius is included on all edges of the ramp to provide a controlled surface for the rover and its tether to move in the event it slides on the lander deck.

7. THE AXEL SYSTEM

The baseline Axel System consists of the Axel Rover with its instrument payload, the lander interface box and the tether (Figure 12). The solar-powered lander trickle charges the rover battery through the umbilical. Power is delivered to the rover through a step-up converter in the interface box. The lander delivers power to the rover through multiple wire pairs at a low amperage to minimize the losses across the length of the tether. Redundant pairs in the tether provide resiliency to failures in the conductor. The rover carries the surface preparation tool and three instrument types: (1) three cameras with a pair in stereoscopic configuration, (2) a multi-spectral imager, and (3) an alpha-particle X-ray spectrometer. All but the three cameras are mounted and deployed from the instrument bays that are engulfed and protected by cantilevered wheels.

8. THE AXEL ROVER

Background

The development of robots for exploring extreme planetary terrains dates back several decades and helped further our understanding of mobility in such terrains [27][28][29][30][31][32][33]. The concept of a minimally actuated rover for planetary exploration emerged as far back as the 1970s. The Axel rover system was independently conceived in 1999 [34]. On very steep slopes like lunar pits, some form of tethering or wall anchoring is necessary to maintain stability. While wall anchoring may be viable in the future to provide more flexible maneuvering and ensure terrain contact for overhangs, *in situ* anchoring on the pit wall would be dependent on knowledge and stability of the rock/terrain properties [35], which can be difficult to characterize *a priori*. Alternatively, tethering tends to provide more stability on steep slopes and reduces risk compared to alternate approaches. However, tethered robots impose constraints on the rover's lateral motion. As such, for near vertical walls, a tethered rover should remain in line with the descent path to avoid lateral forces on the tether that could tug on the rover and cause slip.

A number of tethered robots have been fielded over the past decades [28][29][30][32][36][37][38] and much was learned about tethered mobility in extreme terrains. In 2006, the original Axel rover [39] was retrofitted with a tether and science bays and adapted with grouser wheels for extreme terrain mobility on slopes.

The Axel Rover

Axel is a two-wheeled rover with two large wheel-encased science bays and a boom (Figure 14 and Figure 15). The boom serves multiple functions: (a) it provides the necessary reaction force on the ground for forward mobility on relatively flat terrains, (b) its continuous rotation around Axel's body provides redundancy for the spool and wheel actuators allowing secondary spooling and impaired mobility in case of a failure of any of these actuators, (c) it allows for

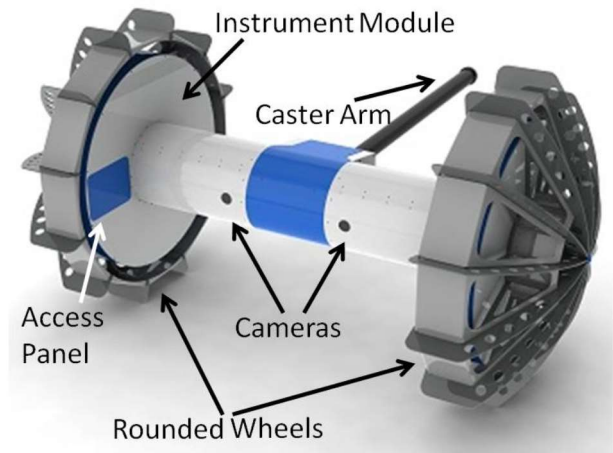


Figure 14: CAD rendering of Axel (version 3) with key features labeled.

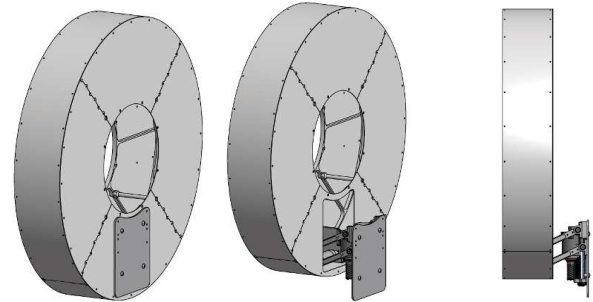


Figure 13: Instrument bays with instrument deployment mechanism

pointing the instruments, and (d) it reduces tether entanglement. Using the Axel-mounted umbilical/ tether, Axel is capable of accessing extreme terrains including vertical walls and overhangs, operating like a motorized yoyo. Using its large grouser wheels, it is capable of traversing obstacles that are a wheel radius in height without the aid of its tether. Its symmetric design enables it to operate from an inverted position. The use of an umbilical not only provides mechanical support, but also provides power and communication to the rover.

The Axel rover is unique in that it combines mobility and manipulation functionalities into a minimally-actuated platform. The science bays on the Axel rover operate in a similar fashion to the boom-mounted turrets on the MER and MSL rover [40], which are populated with science instruments. In essence, Axel is a mobile science platform capable of placing and orienting instruments on sloped targets. Figure 15 shows the Axel rover with a deployed instrument acquiring spectroscopic measurements and microscopic images on stratigraphic layers of a 40° slope at Black Point Lava Flow in Arizona. A single Axel can carry six to eight science instruments and sampling tools in its science bays. However, for the Moon Diver Axel rover, only three instruments are mounted in the bays: the surface

preparation tool, the multi-spectral imager, and the alpha-particle X-ray spectrometer.

Current Axel Prototypes

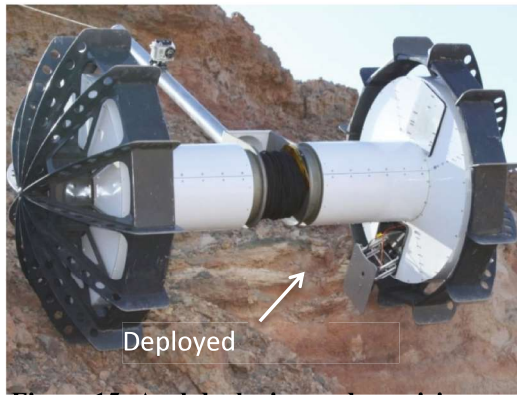


Figure 15: Axel deploying and acquiring infrared spectroscopic measurements and microscopic images from its instrument bay on exposed strata (40° slope).

Several Axel research prototypes have been developed and fielded: an earlier 22 kg version that used the boom for spooling and unspooling the tether, and later 40 kg and 55 kg versions that incorporated an additional actuator to allow full pointing on vertical slopes. Figure 16 shows the conceptual design of a more recent version of the Axel rover prototype. With the 22 kg Axel, we have demonstrated mobility on short vertical cliff walls of a few meters in height [41].

Transitioning from an overhang to a sloped or flat terrain presents a major challenge for robots because one cannot predict which way they will land. This requires the robot to operate from an inverted position. To meet this requirement, we designed Axel to be symmetrical, thus giving it the ability to operate upside down and right side up without added complexity.

The prototype Axel was designed to survive a ½ meter drop in Earth's gravity, and all components and materials used in the rover have been upgraded to comply with JPL safety standards.

Actuation and Mobility

The latest version of Axel uses four primary actuators: one to drive each wheel, one to rotate the boom around the body and a fourth to rotate the spool [42]. With differential driving, Axel can drive forward and backwards, turn in place and traverse arbitrary paths. It can also operate from an inverted position. The boom rotates 360° around the body and serves multiple purposes. It provides a reaction lever boom against wheel thrust to drive the rover. When combined with the motion of the wheels, it controls the rover's pitch to point the body-mounted sensors and instruments. Axel can point its instruments on flat and sloped terrains. The boom also provides a conduit for the tether to prevent entanglement with the wheels. Running the tether through the boom gives Axel greater stability and provides a restoring force for the boom, keeping it off the ground for the most part during steep slope operations. The boom actuator provides some level of redundancy enabling limited mobility following a failure of either or both drive wheels. Driving the boom actuator into

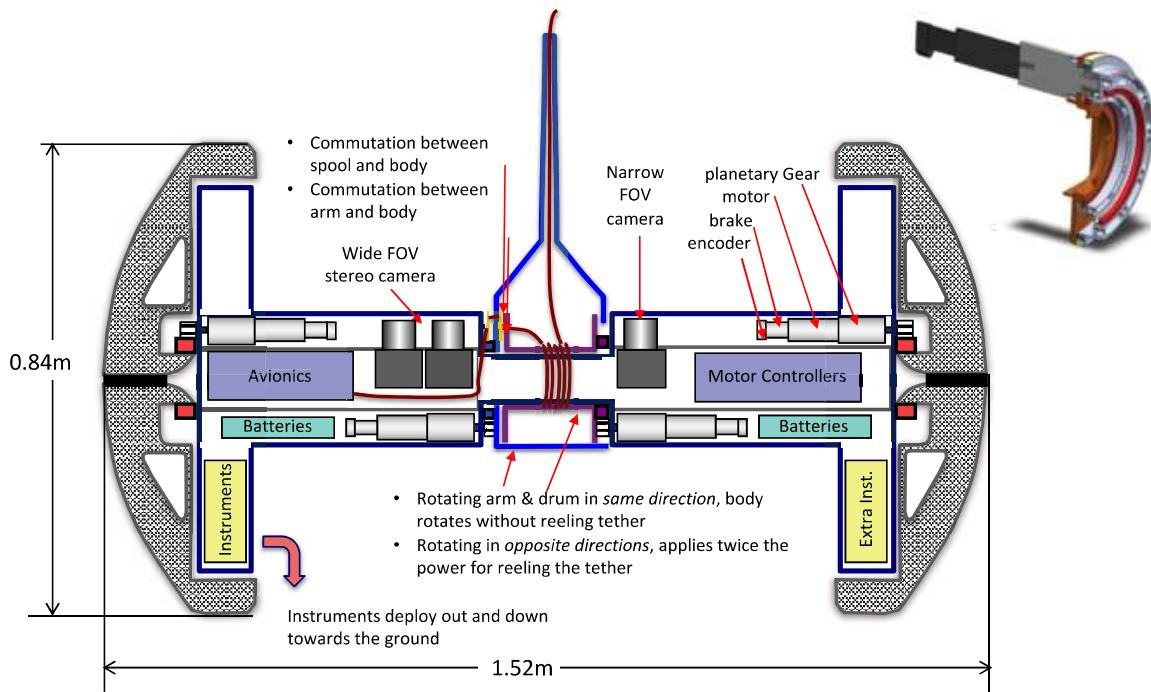


Figure 16: System concept for the Axel v3 rover

the ground will rotate Axel's body and wheels relative to the boom resulting in straight motion. This mode can be used to roll Axel off rocks if it high-centers.

The fourth actuator rotates the tether spool independent of the boom and the body. By coordinating the motion of all four actuators, Axel can point its instruments while remaining stationary on vertical slopes (rotating both the spool drum and boom in the same direction). Rotating the spool drum and the boom in opposite directions would double the power that is applied to the reeling of the tether and hence pulling the rover over very challenging terrain on the ascent.

Figure 16 shows a cross section of the Axel rover. The rotation axes of all four actuators are aligned to provide the versatile functionality and redundancy as previously described. The actuators are brushless DC servo motors with a safety brake, an incremental encoder, and a gear train. The brake uses a power-to-disengage electromagnet, which does not draw any power when the actuator is not in use. In the event of a power failure during motion, the brakes will spring close and prevent the actuators from back driving. The wheel motors drive four-stage planetary gearboxes while the tether drum and caster boom motors drive three-stage planetary gearboxes. A final spur gear pass is on the output of each of the four actuators. This spur pass allows the motors to be mounted off of the rover's body axis and permits the passage of the harness through the center of the rover. The output spur pass and associated thin section bearings are protected from dust intrusion via a three-stage sealing strategy. This sealing system (derived from the MSL and MER rovers) consists of an outermost Nomex felt seal and an inner spring-energized graphite impregnated teflon seal separated by a labyrinth machined into the associated mounting hardware. The wheel actuators are capable of driving speed of 10 cm/s. The tether drum and boom actuators can generate ascent speed of 10 cm/s. In addition to the four primary actuators, secondary actuators are used to deploy instruments and to control the level winding of the tether onto Axel's spool.

Science modules

The larger cylinders within the volume of the wheel structure provide space to house scientific instruments and sampling devices. These are referred to as the instrument modules or science bays (Figure 13). Inside these enclosures and beneath the wheels, the instruments are protected from rocks, protrusions, dust, and falling debris. The opening of a motorized access panel allows APXS, MMI and surface preparation tool to extend out of the wheel structure so that it can be placed within centimeters of the surface. Thus, Axel can take multiple measurements on any slope including vertical. Based on field test results, placement accuracy and repeatability for multiple instruments within a single bay is within millimeters.

Computational module

Axel's central body houses its avionics, which includes the compute element, the motor controllers, the power management system (switching and voltage control). It also houses the communication board, an inertial measurement unit, and a tether tension sensor. The EECAMs would provide stereoscopic images with a baseline of approximately 15 cm depending on its final configuration.

Wheels and tether

The instrument bays are protected with cantilevered wheels. The outboard wheel surfaces are curved so that Axel can roll back to its nominal stance in the case of a tip-over onto its side. Axel wheels have large grousers for going over obstacles [43]. The holes in the grousers reduce wheel mass without compromising overall strength of the wheel structure.

The tether provides mechanical support, power and communication from the lander to the Axel. Its design includes an inner core for structural integrity, an outer layer of helically wound insulated copper wires, a strength member surrounding the conductors, an abrasion layer to protect the tether from the abrasive rocks and regolith and a finish to provide ultra-violet exposure protection. The wires in the tether provide redundancy for both power and communication. The solar-powered lander would provide power to trickle charge batteries inside the Axel through the umbilical tether throughout the surface mission. With a lander panel in sunlight, the rover can operate in the dark recesses of the possible cave, should one exist and should there be enough time within the single lunar day to reach it. Furthermore, redundant power and communication lines ensure continued operation with one or more conductor losses.

Several tether prototypes have been developed and are undergoing lab and field testing to characterize their mechanical and electrical properties. Mechanical tests include characterizing static and dynamic load capability, bending capability, and abrasion resistance, in particular, on sharp basaltic lava and ultra-fine angular regolith under maximum load. A subset of these tests would be performed under simulated lunar conditions: in vacuum, across a temperature range of -50–150 °C, and under full-spectrum UV exposure, equivalent to one lunar day. Electrical tests include characterizing communication bandwidth while delivering 100 W at 300 V through step-up and step-down voltage converters on either end of the 300 m tether. We are testing tethers with 4-, 6-, and 8-wire configurations that are unshielded and helically wound (not twisted pairs). Additionally, we are assessing any adverse effects that electrical transmission may have on the integrated Axel system and flight avionics.

Since the Moon Diver mission is to traverse from the lander to the pit funnel, to its edge and into the pit, the tether would

continuously be paid out as the rover traverses away from the lander. There is no requirement to return the rover to the lander so the tether will largely be paid out without large rewinding on the spool. As such, a complete tether management system, such as the one developed and fielded by Brown et al. [44] would not be necessary for this application. A more minimal design that maintains the unspooled tether and provides tether tension sensing (similar to the original Axel design) should suffice. The enclosure over the cable drum protects the tether from dust and debris, and it also insulates the cable from the environment.

Thermal Design

Axel's design offers some advantages for thermal design and management. All actuators, avionics and instruments are inside the thermally controlled enclosure and, with the exception of the instrument heads, do not have to go through articulated or passive joints. Axel's ability to orient its body can be leveraged to point radiators. One limitation that Axel has is its limited surface area, which impacts the size of the radiators that can be accommodated but radiators that open up increase the surface area for radiation.

For the Moon Diver thermal design, there are three sources for heat loads on the surface: (1) direct solar incidence on the rover, (2) heat reflected from the regolith based on its albedo, and (3) heat dissipated by the rover's instruments and avionics. The heat sink for this application is the cold sky. When the rover is in the pit, infrared emissions from the basaltic wall replace the regolith heat source. An additional heat sink in the pit is the non-illuminated pit wall.



Figure 18: The Axel rover transitioning from the funnel to the wall at the Devolites pit in Arizona.

Experimental Results

Several field tests were conducted with the Axel rover at different sites: (1) at a rock quarry in Canyon Country, California, (2) in the desert near Black Point Lava Flow in Arizona, (3) at mountainous ranges near JPL, and (4) at the basaltic Devolites pit in Arizona. Earlier field tests were conducted using tele-operation with the operator enjoying a bird's-eye view of the rovers. Recent tests were conducted with remote operators using only telemetry to guide the rover's motions. The Devolites campaign includes tests that simulated the operational constraints of the Moon Diver mission concept, which included a remote anchor from the pit edge and simulated operations using rover telemetry and communication rate constraints.

Figure 18 shows the Axel rover descending down the pit wall at the Devolites site. The rover's anchor was 100 m from the pit edge. During these tests, the rover was commanded to traverse tens of meters to the pit edge, acquiring context imaging and navigating solely using telemetry data. The rover was commanded to deploy its instruments and acquire microscopic images of the regolith along the way. The rover transitioned from the flat surface to the funnel with a slope of

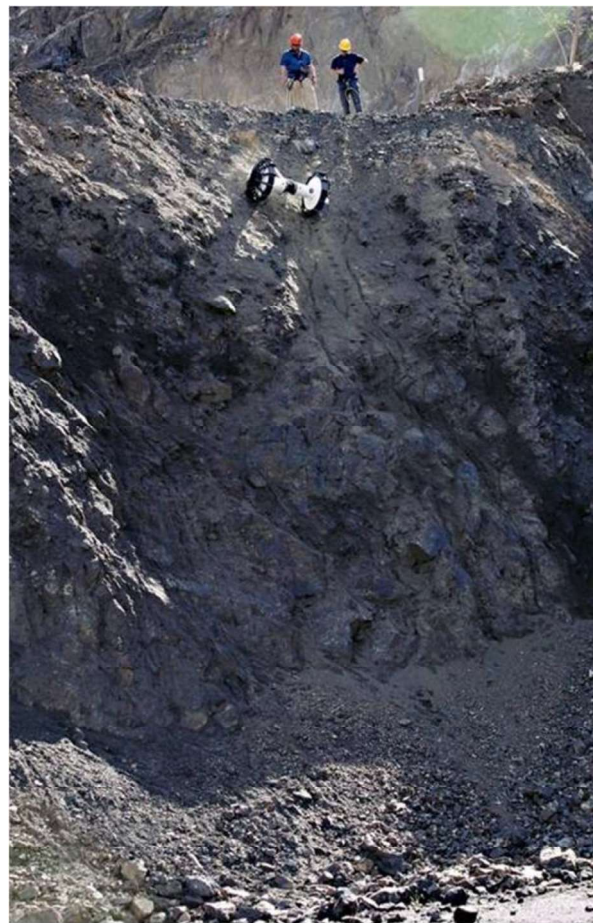


Figure 17: Axel descending a 20 m cliff face with slopes ranging from 65° in angle to near vertical at a quarry in Canyon Country, California.

22°–25°. As the rover traversed the funnel, it was then commanded to transition to a vertical and rocky slope. During these tests, the anchor experienced tensions that reached 400 N with the tether contacting the surface and funnel at a few discrete locations. Due to limited battery life¹, portions of the traverse used line-of-sight operations to speed up the return of the rover but the rover was able to overcome challenging transitions between the funnel and the wall. Note that the Moon Diver mission concept does not require returning the rover to the lander. Over three days, data was collected using the context cameras, the microscopic imager, and the commercial-off-the-shelf X-ray Fluorescence from Bruker on flat, moderately sloped and vertical walls.

An earlier field campaign was conducted in Canyon Country, CA. Figure 17 shows Axel descending a 20-m slope (18 m vertical height) with an anchor several meters from the pit edge. Two full runs were conducted where the rover traversed hard rock, soft soil, and rocky debris. The slope angle of the cliff varied from 65° to near vertical. In both runs, Axel successfully descended across the slope, traversed the flat terrain at the bottom, and returned up the slope. Axel covered a total round trip-distance of 100 m and 50 m during the first and second runs, respectively. Figure 19 shows a time-lapsed sequence of the rover descending the cliff face. With a top speed of 10 cm/s, Axel climbed the 20-m slope in approximately 4 minutes. During some portions of the traverse, large amounts of rocky debris cascaded onto Axel without causing damage to the rover. By controlling the body pitch as it ascended the cliff, the rover effectively protected its cameras from the falling debris.

In another field test in the Arizona desert, Axel rappelled down another steep terrain. The descent slope was 15 m in length with angles that ranged between 25° and 45°. Certain portions of the terrain featuring stratigraphic layers had slope angles between 60° and 78°. Throughout the run, the rover collected measurements with three instruments at intervals specified by a field geologist. At each stop, the rover would re-orient its science instrument module to position different instruments on the target of interest. During this maneuver, there was no visible slip of the rover despite that all four actuators rotating simultaneously to reorient the body. The precision of instrument pointing, on the order of millimeters, was significantly better than our science-driven requirement of 1 cm. During the second test day in Arizona, we conducted two similar excursions on two different slopes: one was a steep slope with relatively few rocks, and the second comprised an easier grade but contained many large scattered rocks. At the top of one of the cliffs there was a fairly steep face at approximately a right angle with the top of the ledge. As the rover ascended this wall, the tether tension reached its peak value of ~760 N for a 53 kg prototype in Earth’s gravity, maintaining a 5× safety factor on the tether capacity.



Figure 19: Time lapsed images of Axel descending a cliff face with slopes ranging from 65° to 85° in angle.

Finally, we conducted a “flip-over” test in the JPL Mars Yard to verify the robustness of the Axel design. We drove the tethered Axel rover up a terrain where a shallow grade ran parallel to a steep grade incline, in order to force a tip-over. As Axel drove up the terrain, straddling the two slopes, one wheel began to rise higher than the other. We continued the ascent until the right wheel flipped over the left wheel and landed on the ground, leaving Axel in an upside-down configuration. The rover is designed to handle such maneuvers and survived the impact without damage and continued to descend successfully under its own power.

In summary, we conducted around a dozen major traverses with Axel over various terrain types and successfully collected a large volume of data both from Axel’s own instruments and the tether tension sensor. These experiments showcased Axel’s ability to navigate challenging terrain and demonstrated end-to-end operational scenarios of the Axel rovers: traversing to a cliff edge, rappelling, measuring, and ascending. Ascending is not required for the Moon Diver mission. Videos from Axel field tests are available at [46].

¹ Electronics for the charging system were not available for this field test.

9. CONCEPT OF OPERATIONS

Moon Diver operations for launch, cruise, descent and landing would be similar to previous missions [40] and so will not be addressed in detail here. By contrast, the Moon Diver surface operations are sufficiently novel that it requires some detailed discussion.

The surface mission would be executed during the lunar sunlit period, providing 300 to 330 hours of operations, with the available duration depending on the local solar time of landing. While many lessons can be drawn and tools can be inherited from Mars surface missions, the command cycle can be more efficient because of the continuous and low-latency (seconds) communication that would enable the mission operations within a single lunar day. The Mars Science Laboratory (MSL) operations team typically uploads an entire sol (24.7 hours) of commands to the Curiosity rover, to be executed end-to-end without human intervention. This requires careful validation of the command sequences, together with conservative resource modeling, to ensure rover health and safety and to avoid command errors. Moon Diver operations would depart from this model, utilizing the short round-trip light time to the moon to enable continuous commanding of the Axel rover.

The Moon Diver lander would be continuously awake during the surface mission, serving as a stable platform for rover operations. Once landed and checked out, the lander's primary tasks are solar array tracking and maintaining the communications link between ground operators and the rover. These tasks require only occasional commanding, perhaps no more than once per Earth day, for example to modify an ephemeris file or optimize array performance. By contrast, the rover command cycle would be as short as 2 minutes. The high bandwidth and close proximity of the Moon enables rover telemetry, navigation images, and decisional science data to be made available with low latency (10s of seconds) to the ground team. Commands would be uplinked one or a few at a time to the rover, with the result of the commands known on the ground before the next bundle is sent. During rover operations, the lander would immediately forward rover data to Earth and pass commands from Earth through to the rover.

This mode of continuous rover operations has been extensively exercised at JPL in the MSL and Mars 2020 testbeds, including commanding of rover traverse and instrument operations. As such, ground tools, including the Rover Sequencing and Visualization Program (RSVP) suite, have already been adapted for this mode. RSVP enables selection and visualization of traverse arcs, automation of command sequence writing and validation, and the display of real-time rover telemetry.

The mission is designed so that the instantaneous resources required for operations have excess margin above worst-case expected scenarios, providing power, bandwidth, and temperature margin. This effectively decouples the lander

and rover resource models, enabling the lander and rover teams to operate in a nominally independent way, and for rover operators to make decisions without the delay of simulating rover performance in real time. Operators may then focus on completing the mission goals against the only remaining constrained resource, which is the available mission duration.

During the surface phase, Moon Diver mission operations would be staffed around the clock with rotating shifts. A trio of Rover Operator, Science Operator, and a Lead role would interface directly with the uplink tools, commanding the rover. They would be supported by an adjacent room of scientists and engineers, with dedicated channels of communications between the rooms as a means to avoid distractions. Human factors would be informed as much by the lessons of human spaceflight as those of Mars robotic operations.

10. SUMMARY

The Moon Diver mission concept takes advantage of the discovery of a natural pit that exposes a deep cross-section of lunar stratigraphy and two advances in capabilities: pinpoint landing and extreme terrain mobility to conduct a science investigation that would deepen our understanding of fundamental processes for secondary crusts on the Moon, and to use this knowledge as a keystone for understanding the same processes across the Solar System. It would provide the first *in-situ* observations of secondary crust bedrock on a single-plate planet. Using the rover's instrument suite, we would learn about context, elemental composition, and mineralogy to understand the composition, emplacement, and regolith formation of these secondary crusts.

11. ACKNOWLEDGMENTS

This work is a joint collaboration between Caltech and the Jet Propulsion Laboratory. The work was done at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration. The information presented about the Moon Diver mission concept is pre-decisional and is provided for planning and discussion purposes only.

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13. BIOGRAPHY



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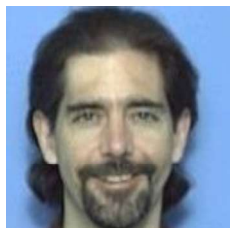


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Andrew Johnson, Ph.D. is a principal technology at the Jet Propulsion Laboratory and the Principal Investigator for terrain relative navigation. He graduated with Highest Distinction from the University of Kansas in 1991 with a BS in Engineering Physics and a BS in Mathematics. In 1997, he received his Ph.D. from the

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Matt Heverly is the supervisor for the mechanisms group at the Jet Propulsion Laboratory. He joined JPL in the spring of 2005. Prior to this, Matt worked at an industrial aerospace company designing robotic hardware and space mechanisms. Matt is currently working as a mobility systems engineer for the Mars Science Laboratory (MSL) rover. Prior to this he was the chief mechanical engineer on the ATHLETE hex legged rover as well as a Rover Driver on the "Opportunity" Mars Exploration Rover.



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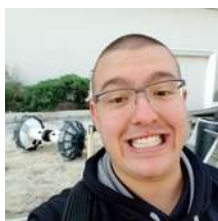


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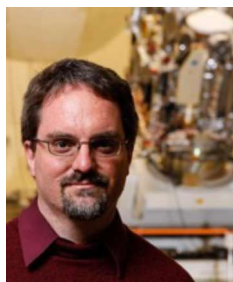
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